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ABSTRACT

A study has been conducted to determine the effects of seventh-stage compressor bleed on the performance of the F100 afterburning turbofan engine. The effects of bleed on thrust, specific fuel consumption, fan turbine inlet temperature, bleed total pressure, and bleed total temperature were obtained from the engine manufacturer's status deck computer simulation for power settings of intermediate, partial afterburning, and maximum afterburning; for Mach numbers between 0.6 and 2.2; and for altitudes of 30,000, 40,000, and 50,000 ft. It was found that thrust loss and specific fuel consumption increase were approximately linear functions of bleed flow, and, based on a percent-thrust change basis, were approximately independent of power setting.

INTRODUCTION

Bleed air is often extracted from a jet engine's compressor for various applications during aircraft flight. These applications include fuel tank pressurization, environmental control system use, anti-icing systems, aerodynamic blowing, and driving compressors and suction pumps. This extraction of bleed air introduces a performance penalty on the engine. Bleed usually causes thrust to decrease, specific fuel consumption to increase, and engine turbine temperatures to increase. All of these parameters have a strong effect on aircraft performance.

For laminar flow control systems, bleed air from the engine compressor may be required for powering suction pumps. The effects of such bleed need to be considered during the conceptual design of laminar flow control systems.

Therefore, a study has been conducted at the NASA Ames Research Center's Dryden Flight Research Facility to determine the impact of various levels of compressor bleed on the performance of the F100-PW-220 afterburning turbofan. Interstage bleed taken off at the 7th stage was considered in this study, although 13th stage bleed is also available on the F100 engine. The Pratt & Whitney steady-state mathematical model, reference 1, was used to determine the response of the F100-PW-220 engine to the various levels of interstage bleed for this study. Bleed flow was varied from 0 to approximately 2.6 percent of compressor flow, and the changes in thrust, specific fuel consumption (SFC), engine temperatures and pressures and engine turbine temperatures were examined.

This paper presents the results of the interstage bleed effects for a range of Mach numbers from 0.6 to 2.2, for intermediate (maximum nonafterburning) power, partial afterburning, and maximum afterburning for altitudes of 30,000, 40,000, and 50,000 ft for standard day conditions.

NOMENCLATURE

DEEC	digital electronic engine control
FN	net thrust, lb
FTIT	fan turbine inlet temperature, °F
h	altitude, ft

M	Mach number
PLA	power lever angle, deg
PCTBL	compressor air flow used for bleed air, percent
PTBI	total pressure of interstage bleed, PSIA
SFC	specific fuel consumption, lbm/hr/lbf
TTBI	total temperature of interstage bleed, °F
WBI	seventh-stage compressor bleed air flow rate, lb/sec

DESCRIPTION OF EQUIPMENT

Engine Description

The F100-PW-220 engine, figure 1, is a two-spool low-bypass ratio-augmented turbofan engine, built by Pratt and Whitney, West Palm Beach, FL. This engine consists of a 3-stage fan, 10-stage compressor, combustor, 2-stage high-pressure turbine, and a 2-stage low-pressure turbine. A mixed-flow augmentor exhausts through a balanced-beam nozzle. The F100-PW-220 engine is equipped with a digital electronic engine control (DEEC), reference 2.

For the F100-PW-220 engine, the compressor bleed may be extracted from the 7th stage (interstage bleed) or 13th stage (customer bleed). The bleed source varies with Mach number and altitude. At high power settings and speeds typical of supersonic aircraft, the 7th stage bleed would normally be used. For this report all bleed air is assumed to be from the 7th stage (interstage) of the compressor, as shown in the inset in figure 1.

F100 Engine Simulation Program (Status Deck)

Pratt & Whitney Aircraft Customer Computer Deck (CCD 1148-0.0) is a steady-state mathematical model of the Pratt & Whitney F100-PW-200 engine, equipped with a DEEC which utilizes DEEC PD 2.3 logic. This computer simulation closely approximates the F100-PW-220 engine that powers the F-15 and F-16 airplanes.

The function of this simulation program is to predict engine performance by using the characteristics of the engine's eight components (fan, compressor, primary combustor, high-pressure turbine and fan turbine, augmentor, exit nozzle, and fan duct). The values for pressures, temperatures, and mass flows throughout the engine are determined through the use of aerodynamic and thermodynamic equations. For this report, the amount of interstage bleed was varied from 0 to the maximum capability, which was approximately 2.6 percent of the compressor airflow.

PROCEDURE

The engine simulation program was used to develop the effects of bleed on several engine parameters. Inputs to the engine simulation are Mach, altitude, power level angle (PLA), and bleed flow rate. The Mach and altitude, along with the inlet recovery of the F-16 airplane, specified the engine face pressure and temperature for standard day conditions.

A baseline set of results were obtained from the engine simulation with no bleed. Computer runs were then made with increasing levels of bleed, and the results were ratioed to the no-bleed parameter values. Altitudes of 30,000, 40,000 and 50,000 ft were used. Mach numbers appropriate to each of 3 power settings were used: M = 0.6 to 1.0 for a PLA = 83° (intermediate power); M = 0.6 to 1.6 for PLA = 110° (partial afterburning), and M = 0.6 to 2.2 for PLA = 130° (maximum afterburning).

Data are displayed with calculated data points shown with symbols and straight lines drawn in between; some uncertainty may result as to where points should lie in between data points.

Since the results are presented as percent changes, the results are applicable to other airplanes powered by the F100 series engines.

RESULTS AND DISCUSSION

The effects of compressor interstage bleed flow (WBI) on the bleed pressure (PTBI) and temperature (TTBI) and three engine parameters are presented. The engine parameters were net thrust (FN), specific fuel consumption (SFC), and fan turbine inlet temperature (FTIT). These parameters were plotted as a function of Mach number and percent of interstage bleed (PCTBL) for flight conditions between 30,000 and 50,000 ft at PLA's of 83°, 110°, and 130°. PCTBL values ranged from 0 to maximum bleed of approximately 2.6 percent.

Compressor interstage bleed flow rate values in lb/sec at various PLA, Mach number, and altitude conditions are presented in the Table. The compressor airflow was computed by the engine simulation and used to generate the percent bleed flows. These values can be used to convert the percentage bleed flows to absolute mass flows if desired.

Fan Turbine Inlet Temperature, FTIT

Figures 2, 3, and 4 display FTIT as a function of Mach number, PCTBL, and altitude at a PLA of 83°, 110°, and 130°, respectively. At the lower Mach numbers, the DEEC compensates for the bleed extraction by increasing FTIT to maintain the scheduled fan airflow. This increase in FTIT is approximately 20°F for each additional percentage of bleed until the FTIT limit of 1720°F is reached. Once the temperature limit is reached, fan airflow, and hence thrust, will decrease, as will be shown in later figures.

Compressor Interstage Bleed Pressure

Figure 5 shows the effects of Mach number and bleed flow on PTBI for altitudes of 30,000, 40,000, and 50,000 ft at PLA = 83°. Increasing Mach number results in an almost linear increase in PTBI. The first 1 percent of bleed results in a reduction of approximately 3 percent in PTBI, but the second percent of interstage bleed causes about an 8-percent reduction in PTBI. For maximum bleed cases, approximately 15 percent of compressor interstage pressure is lost.

Figure 6 shows the effects of Mach number and altitude and PCTBL on PTBI for a PLA = 110°. Results are very similar to the PLA = 83° data from figure 5.

Figure 7 shows the effects of Mach number and altitude and PCTBL on PTBI for PLA = 130°. At the lower Mach numbers, the results agree well with the data from the 83° and 110° PLA's, while at the higher Mach numbers above M = 1.8, PTBI increases less with increasing Mach.

Compressor Interstage Bleed Temperature

Compressor interstage bleed temperature, TTBI, is shown in figure 8 as a function of Mach number, altitude, and PCTBL at a PLA of 83°. TTBI increases with Mach number, and decreases slightly with altitude, mostly due to the change in engine inlet temperature. As can be seen, PCTBL had only a minor effect on TTBL, at most approximately 10°F.

Effects at a PLA of 110° and 130° are shown in figures 9 and 10, respectively, and show the same trends shown in figure 8. At altitudes of 50,000 ft, PCTBL effects TTBI by only approximately 2°F. Figure 10 shows that at high Mach numbers, TTBI values become high; at Mach 2.0, TTBI is above 700°F.

Net Thrust

The effect of Mach number, PCTBL, and altitude on change in net thrust (FN) is shown in figure 11 at a PLA of 83°. At flight conditions where the engine is operating below the FTIT limit (M = 0.7 at h = 30,000 ft, fig 11 a; M = 0.9 at 40,000 ft, fig 11 b; and M = 1.0 at 50,000 ft, fig 11 c), increasing bleed has only a small effect on thrust (approximately 0.2 percent loss in thrust per PCTBL). Once the FTIT limit is reached, the effects of the engine control system are quite significant and thrust decreases rapidly. For altitudes of 30,000 and 40,000 ft, reductions of over 6 percent are shown for maximum bleed cases. However at 50,000 ft, the FTIT limit is never reached and a decrease of only 0.5 percent occurs for maximum bleed cases.

Figure 12 shows the effects of Mach number, PCTBL, and altitude on FN at PLA = 110°. Results are somewhat similar to the PLA = 83° results. However, the afterburner fuel pump uses engine bleed air, which results in an increased loss of thrust. This loss below the FTIT-limiting Mach number is as high as 1 percent, and above the FTIT limiting Mach number, it exceeds 6 percent.

Figure 13 shows how FN reacts to Mach number, PCTBL, and altitude, at full afterburning, PLA = 130°. Results are similar to those in figure 12, except in the Mach 1.4 to 1.8 range, where some augmentor segment changes occur. Again, the afterburner fuel pump requires more bleed air so an additional reduction of FN occurs. FN is reduced up to 7 percent for maximum bleed cases.

Figure 14 displays percent change in FN as a function of PCTBL at h = 40,000 ft and PLA = 110° and 130°. From this figure it can be seen that FN decreases linearly with increasing bleed, and that the thrust loss is much greater at supersonic Mach numbers. At maximum bleed, approximately 6 percent of net thrust is lost.

Percent change in net thrust was found to be almost independent of PLA setting. This can be seen in Figure 15 where percent change in net thrust is plotted as a function of Mach number at an altitude of 30,000 ft and a bleed extraction of 1 percent for a three power settings. The values for percent change in net thrust are found to correspond fairly closely for each PLA setting.

Specific Fuel Consumption, SFC

SFC is analyzed as a function of Mach number, PCTBL, and altitude in figures 16, 17, and 18. Figure 16 shows that at a PLA of 83°, SFC increases, on the average, 1.5 percent for each percent of increased bleed. The largest percentage increase in SFC for this power setting was approximately 4 percent, and this always occurred for maximum bleed settings.

In figure 17, the FTIT limit is found to affect the results again. Below this limit (about M = 1.2) SFC increases approximately 0.7 to 0.9 percent for each percentage of bleed extraction, and above this limit, SFC increases approximately 1.2 to 1.4 percent per percent of bleed extraction. At 50,000 ft, SFC increases approximately 0.8 percent for each percent increase in PCTBL.

At full afterburner (fig. 18), SFC reacted similarly for altitudes of 30,000 and 40,000 ft. In both cases, bleed had the biggest effect on SFC at M = 1.4, where each percentage increase in bleed increased SFC by approximately 1.5 percent. Maximum bleed settings at this point caused a 4.2- and 3.8-percent increase in SFC at altitudes of 30,000 and 40,000 ft, respectively. At 50,000 ft, bleed had a smaller effect on SFC. The most sensitive case is M = 2.2; SFC increases by approximately 1 percent for the first percent of bleed, and by approximately 1.3 percent for the second percent of bleed. The biggest increase in SFC occurs at this Mach number for the maximum bleed setting, in which case SFC increases by about 3 percent.

Figure 19 displays percent change in SFC as a function of PCTBL at 40,000 ft and PLA's of 110° and 130°. It can be seen that this relationship is linear, with a greater increase in SFC for larger Mach numbers. An approximate 3.8 percent increase in SFC occurs at higher Mach numbers.

CONCLUDING REMARKS

A bleed study was performed on an F100-PW-220 engine using a Pratt & Whitney status deck as a mathematical model. Interstage bleed pressure, interstage bleed temperature, net thrust, specific fuel consumption, and fan turbine inlet temperature were examined as a function of percent bleed at several flight conditions.

The DEEC was found to compensate for bleed extraction by increasing FTIT to hold a constant fan airflow. This increase in FTIT was approximately 20°F per percent of bleed.

As Mach increased, a FTIT limit of 1720°F was reached, after which FTIT remained essentially constant, and thrust decreased.

It was determined that compressor interstage pressure was decreased by approximately 3 percent for the first 1 percent of bleed, and decreased by approximately 8 percent for the second percent of bleed. Maximum bleed settings resulted in about a 15 percent decrease in PTBI.

Compressor interstage bleed was found to have little effect on TTBI. For the most severe cases (with maximum bleed), TTBI only had 10°F changes.

The reaction of FN to interstage bleed was found to be sensitive to the FTIT limit. Below this limit, FN had little reaction to bleed (about 0.2 percent decrease in FN per percent increase in bleed). Above the FTIT limit, decreases in FN exceeding 6 percent occurred. For the afterburning power settings, a larger decrease in FN, up to 7 percent, was seen.

For SFC increases, at PLA = 83°, SFC would increase on an average 1.5 percent for each additional percent of bleed. For a PLA setting of 110°, SFC is seen to increase 1 percent per percent increase in bleed. Finally, for PLA = 130°, SFC would increase on an average 1.2 percent for each additional percent of bleed.

Both thrust loss and SFC increases were approximately linear with bleed flow. On a "percent thrust change" basis, thrust loss was found to be approximately independent of power setting for the three power settings studied.

REFERENCES

Pratt & Whitney Aircraft Group, F100 Engine Model Derivative Program, *Preliminary JTF 22B-36 Status Deck Users Manual for Deck CCD 1148-0.0*, prepared for the U.S. Air Force under Contract 33657-79-C-0541 by Pratt & Whitney, West Palm Beach, FL, March 1980.

Burcham, F.W. Jr., L.P. Myers, and K.R. Walsh: "Flight Evaluation of a Digital Electronic Engine Control in an F-15 Airplane," AIAA-83-2703, Nov. 1983.

Amount of Interstage Compressor Bleed

PLA (deg)	Bleed % (PCTBL)	WBI (lb/sec)									
		M									
		0.6	0.7	0.8	0.9	1.0	1.2	1.4	1.6	1.8	2.2
83	1%	0.59	0.63	0.68	0.73	0.78					
	2%	1.18	1.27	1.36	1.46	1.54					
	2.61%	1.54	1.65	1.77	1.89	2.00					
110	1%	0.59		0.68		0.77	0.88	0.99	1.05		
	2%	1.18		1.36		1.53	1.73	1.96	2.09		
	2.60%	1.54		1.77		1.97	2.23	2.54	2.71		
130	1%	0.59				0.77		0.99		1.10	1.10
	2%	1.18				1.52		1.96		2.16	2.18
	2.60%	1.54				1.97		2.53		2.79	2.83

(a) h = 30,000 ft.

PLA (deg)	Bleed % (PCTBL)	WBI (lb/sec)									
		M									
		0.6	0.7	0.8	0.9	1.0	1.2	1.4	1.6	1.8	2.2
83	1%	0.37	0.40	0.44	0.48	0.53					
	2%	0.75	0.81	0.88	0.96	1.05					
	2.61%	0.98	1.06	1.15	1.26	1.37					
110	1%	0.37		0.44		0.53	0.59	0.66	0.71		
	2%	0.75		0.88		1.04	1.18	1.31	1.41		
	2.61%	0.98		1.15		1.35	1.52	1.70	1.83		
130	1%	0.39				0.53		0.66		0.75	0.76
	2%	0.78				1.04		1.31		1.47	1.51
	2.61%	1.01				1.35		1.70		1.90	1.95

(b) h = 40,000 ft.

PLA (deg)	Bleed % (PCTBL)	WBI (lb/sec)									
		M									
		0.6	0.7	0.8	0.9	1.0	1.2	1.4	1.6	1.8	2.2
83	1%	0.22	0.24	0.26	0.29	0.31					
	2%	0.45	0.49	0.53	0.57	0.62					
	2.62%	0.59	0.64	0.69	0.75	0.81					
110	1%	0.23		0.26		0.31	0.36	0.40	0.43		
	2%	0.45		0.53		0.62	0.71	0.80	0.85		
	2.62%	0.59		0.69		0.81	0.93	1.04	1.11		
130	1%	0.23				0.32		0.40		0.45	0.46
	2%	0.47				0.64		0.80		0.89	0.91
	2.62%	0.61				0.83		1.03		1.16	1.19

(c) h = 50,000 ft.

Table - WBI as a function of Mach, PCTBL and PLA.

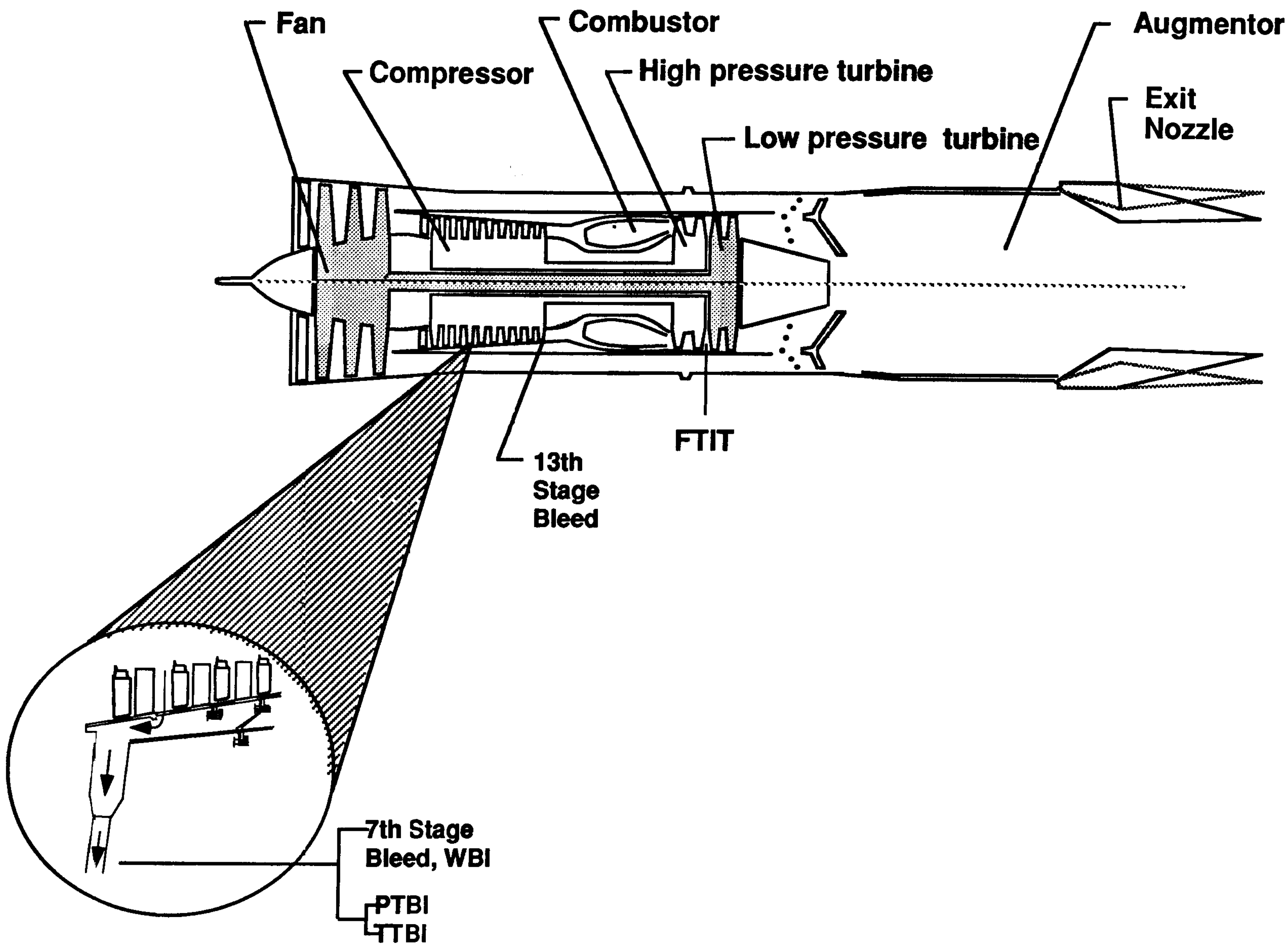
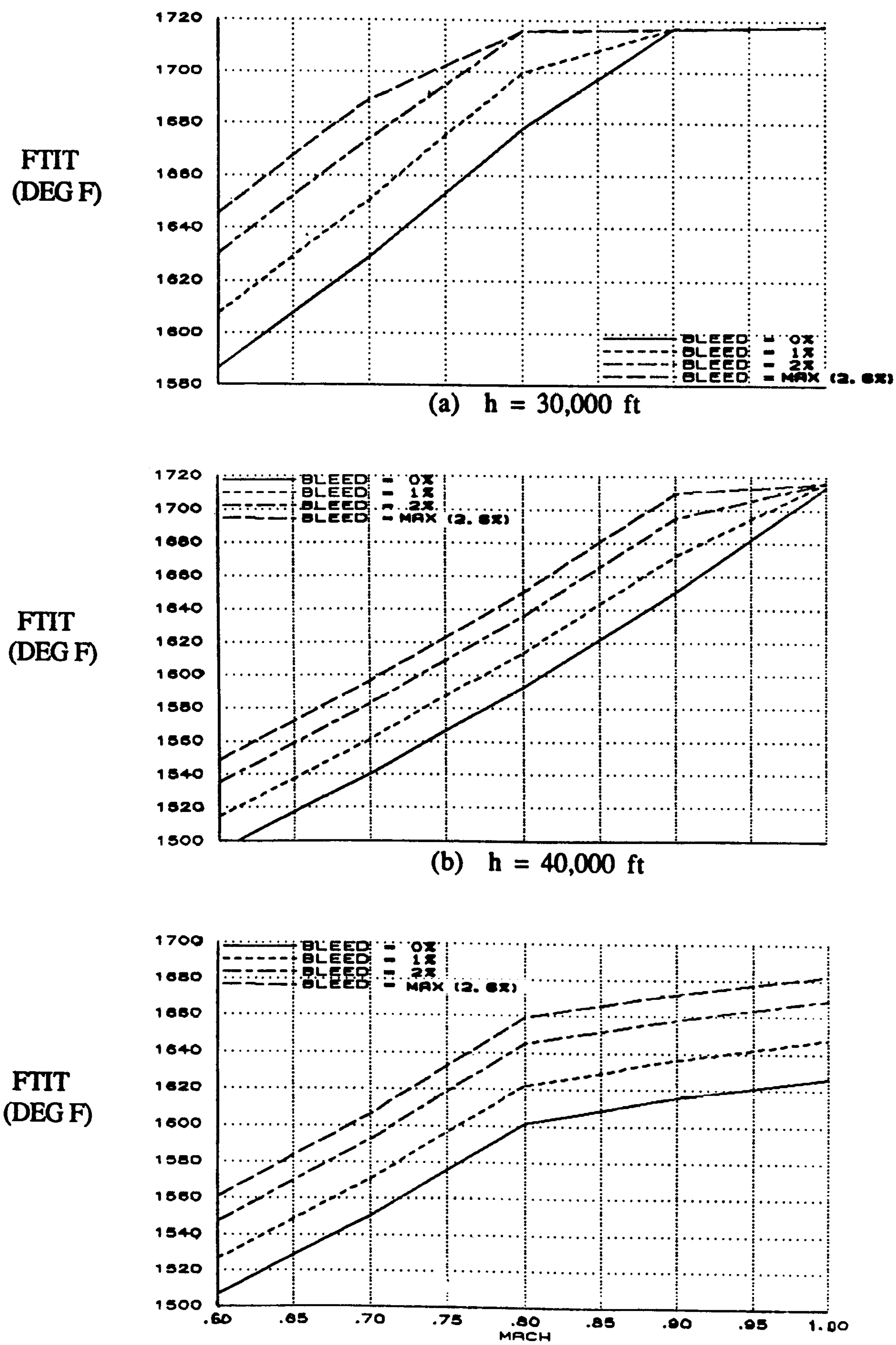


Figure 1. F100 engine showing compressor bleed and related engine parameters.

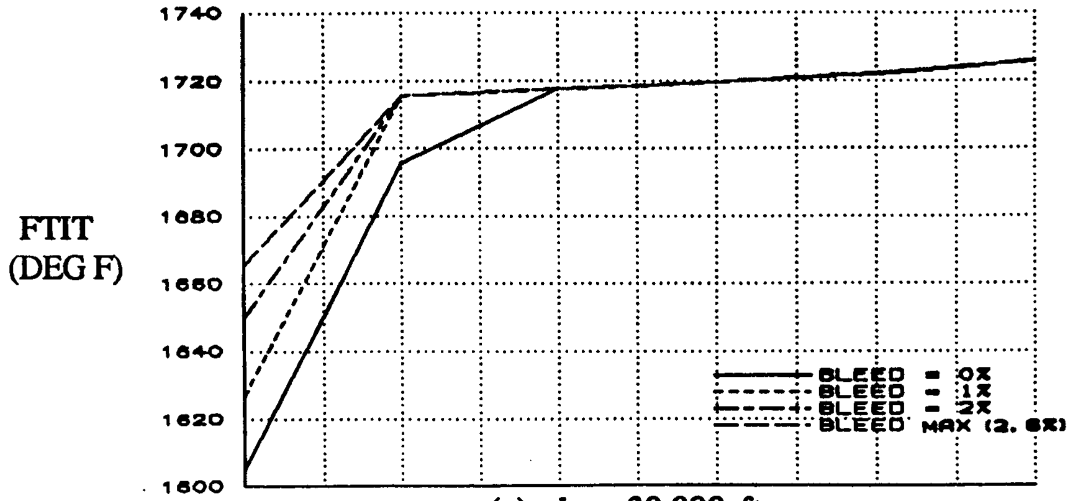


(a) h = 30,000 ft

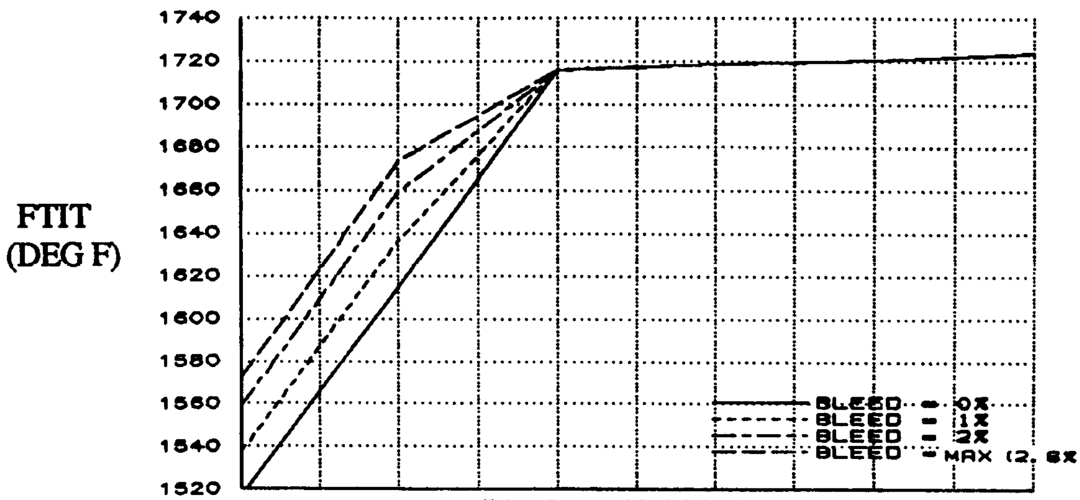
(b) h = 40,000 ft

(c) h = 50,000 ft

Figure 2. The effect of Mach and bleed air flow on FTIT; PLA = 83°.



(a) h = 30,000 ft



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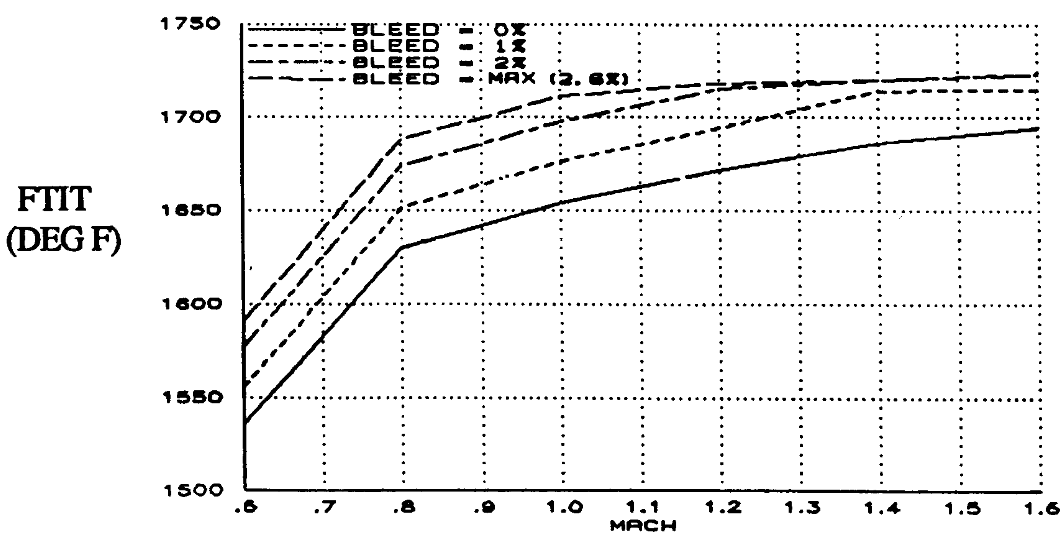
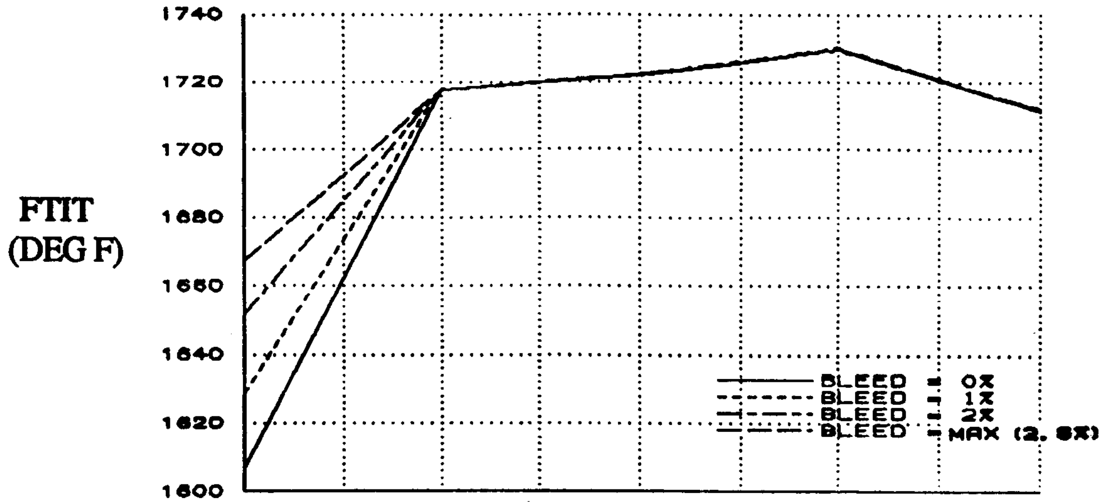
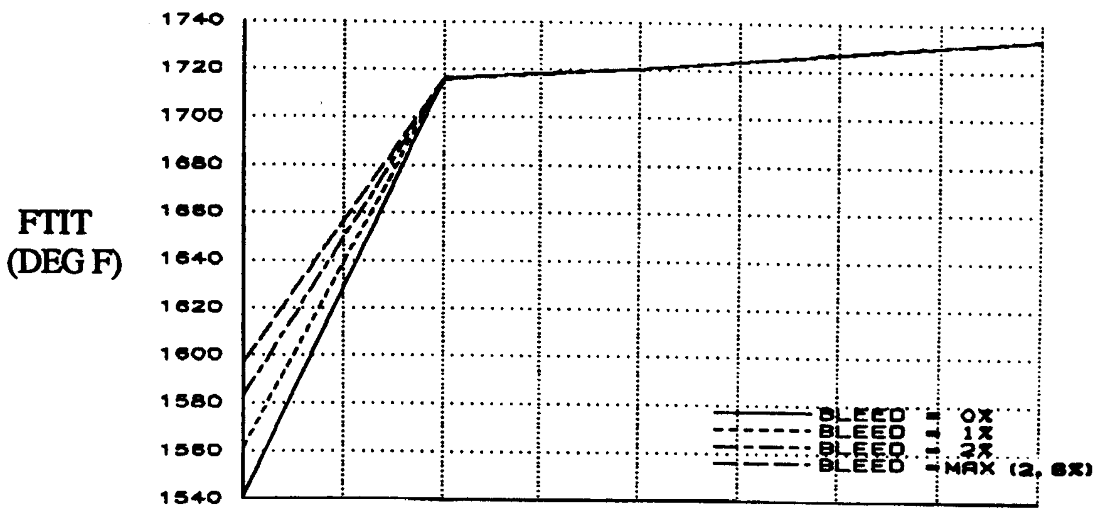


(c) h = 50,000 ft

Figure 3. The effect of Mach and bleed air flow on FTIT; PLA = 110°.



(a) h = 30,000 ft



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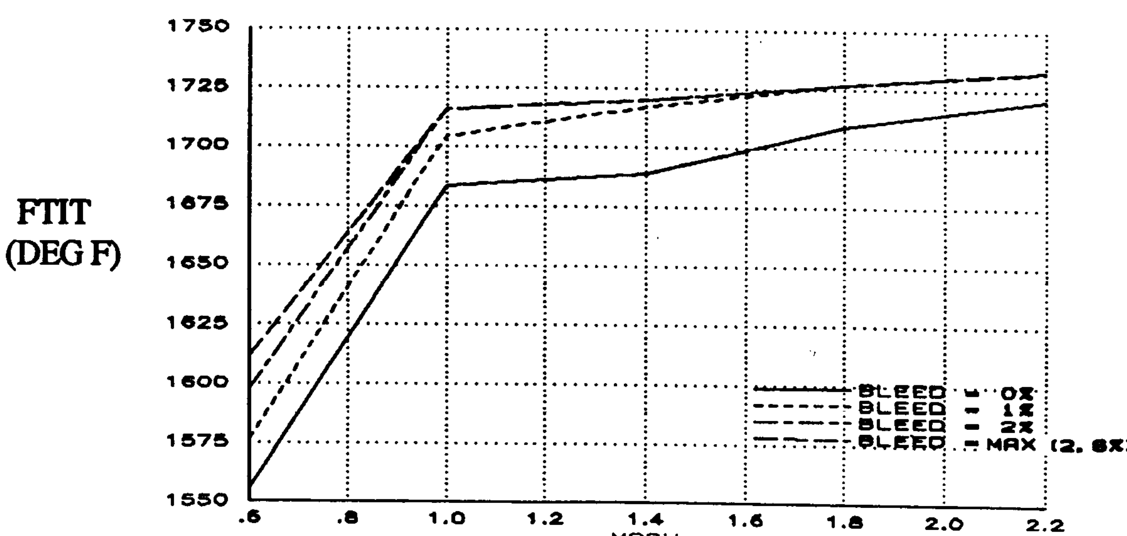
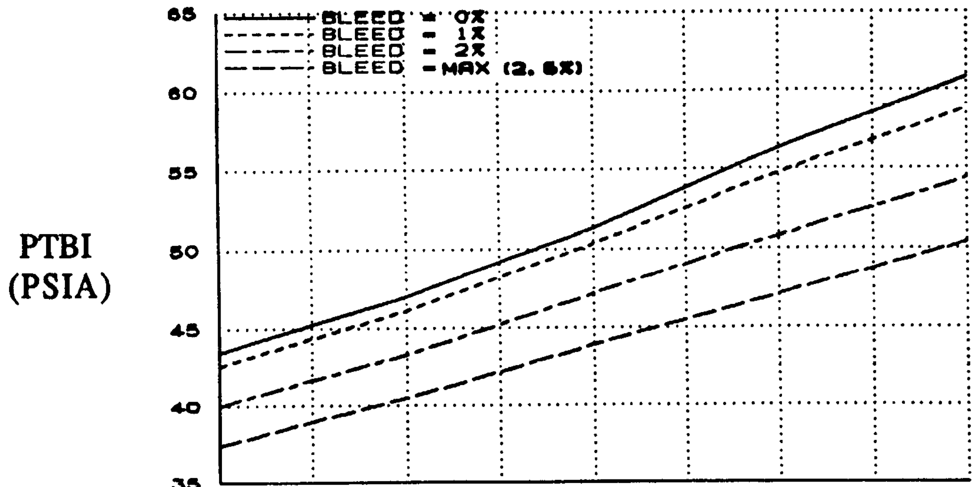
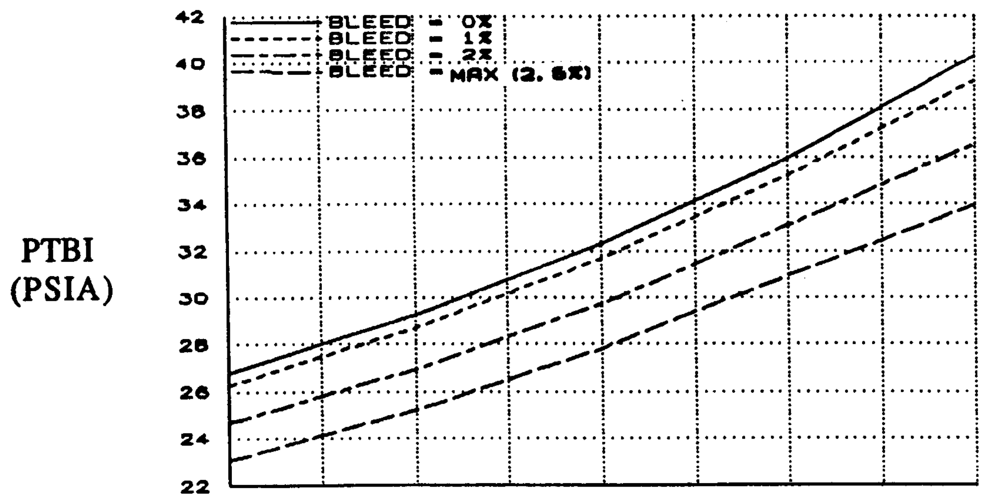


(c) h = 50,000 ft

Figure 4. The effect of Mach and bleed air flow on FTIT; PLA = 130°.



(a) h = 30,000 ft



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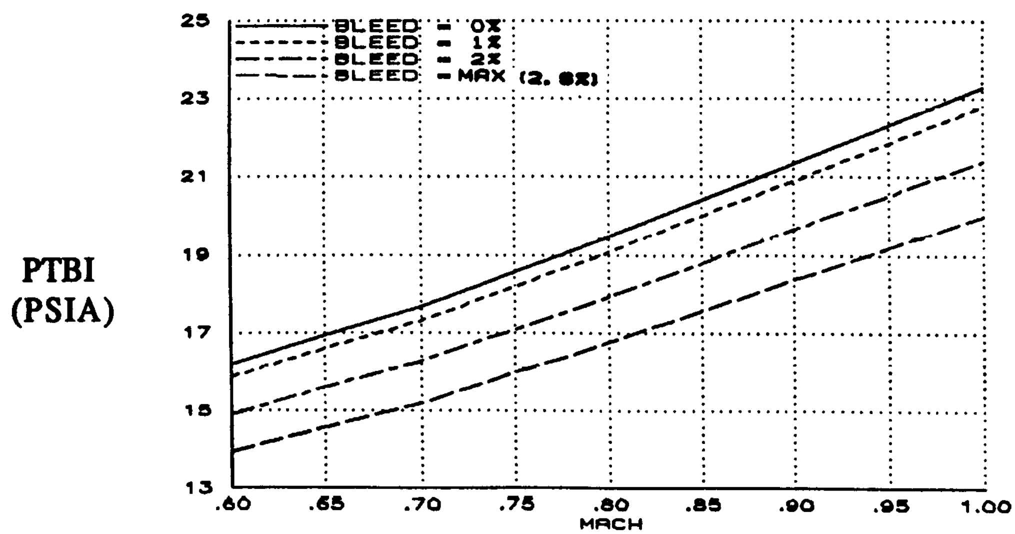
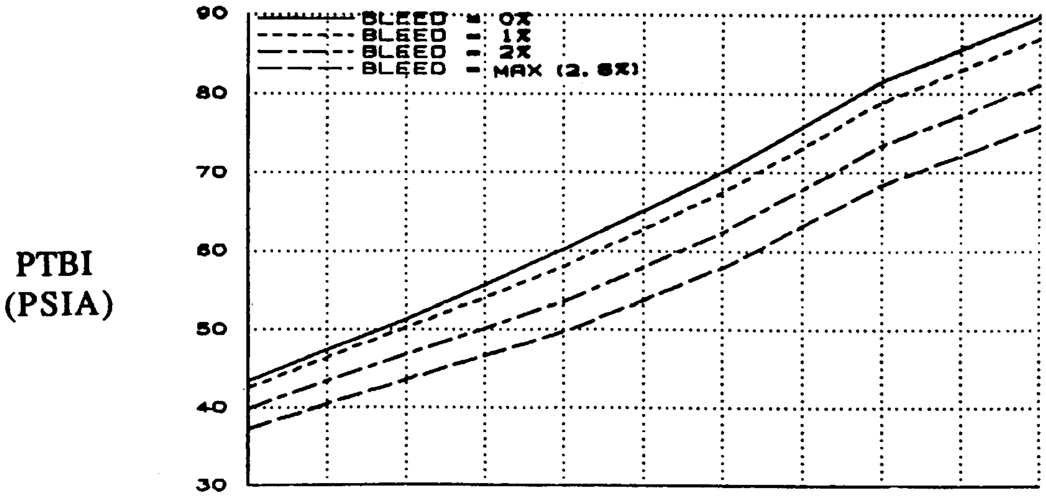


(c) h = 50,000 ft

Figure 5. The effect of Mach and bleed air flow on PTBI; PLA = 83°.



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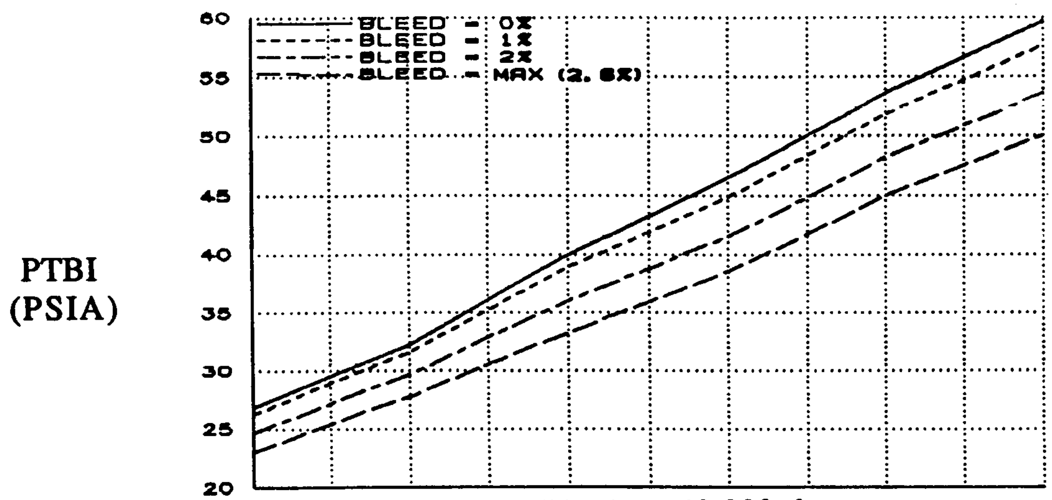

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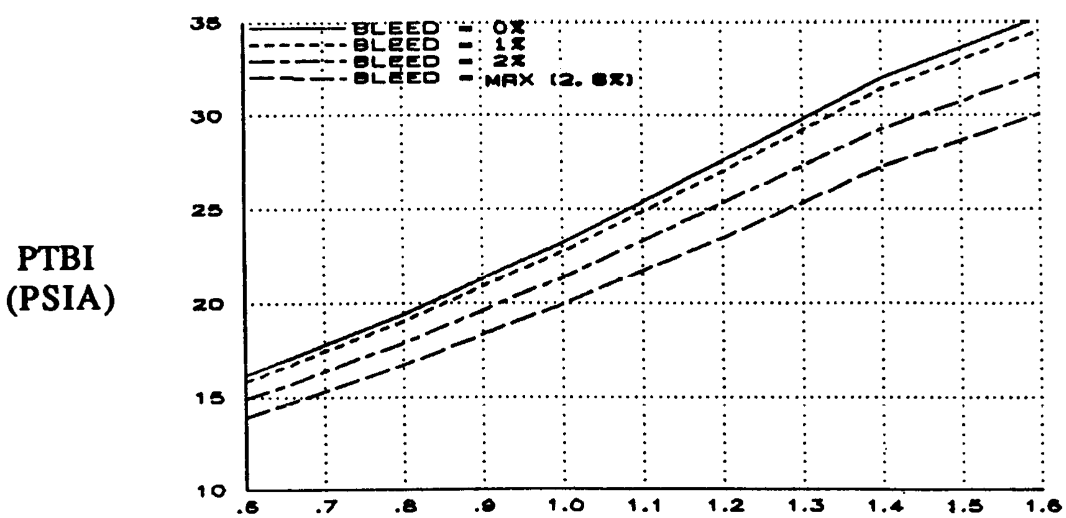
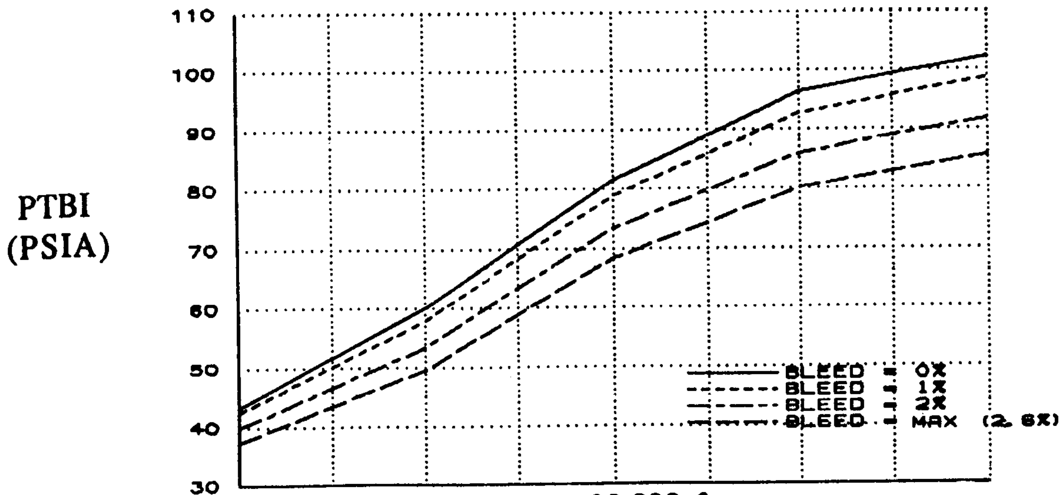


(c) h = 50,000 ft

Figure 6. The effect of Mach and bleed air flow on PTBI; PLA = 110°.



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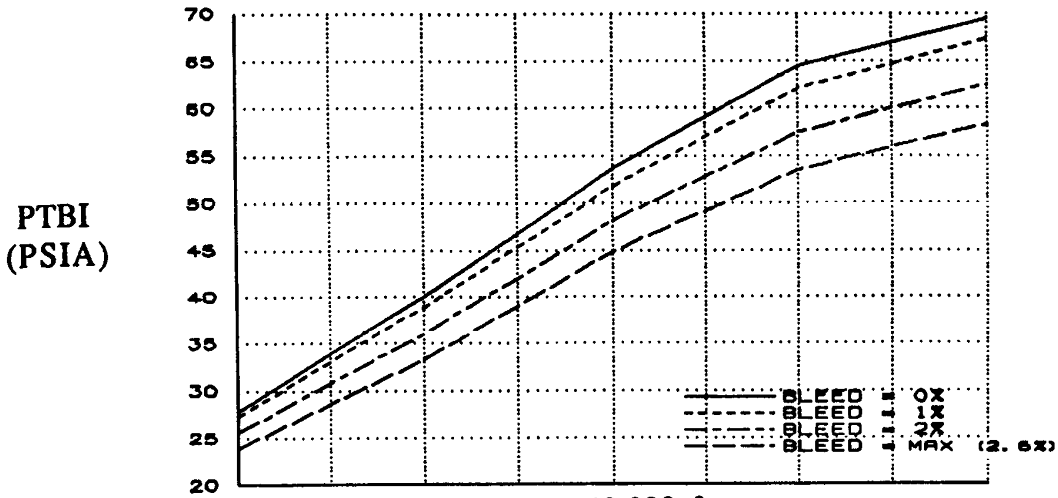

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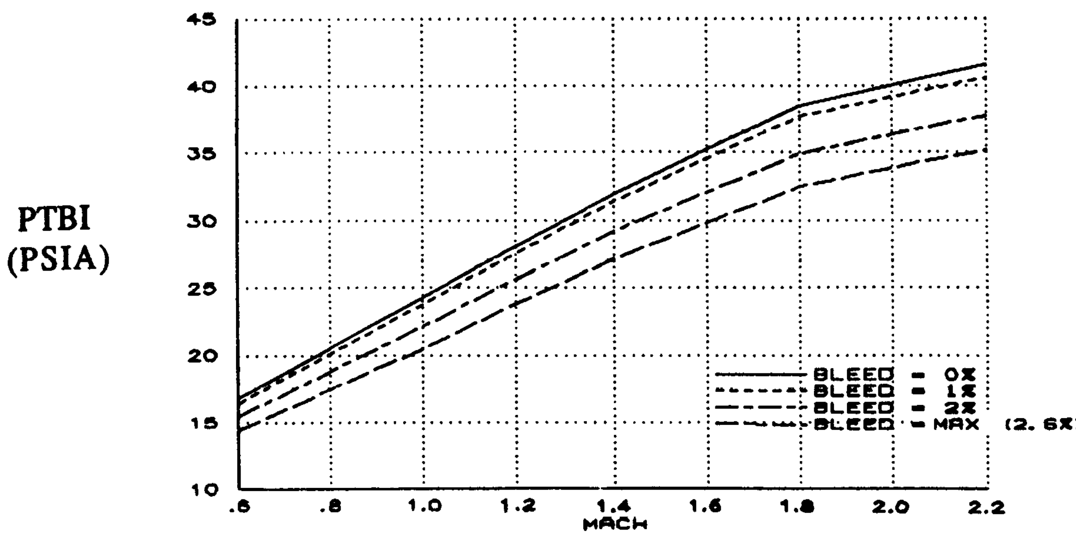
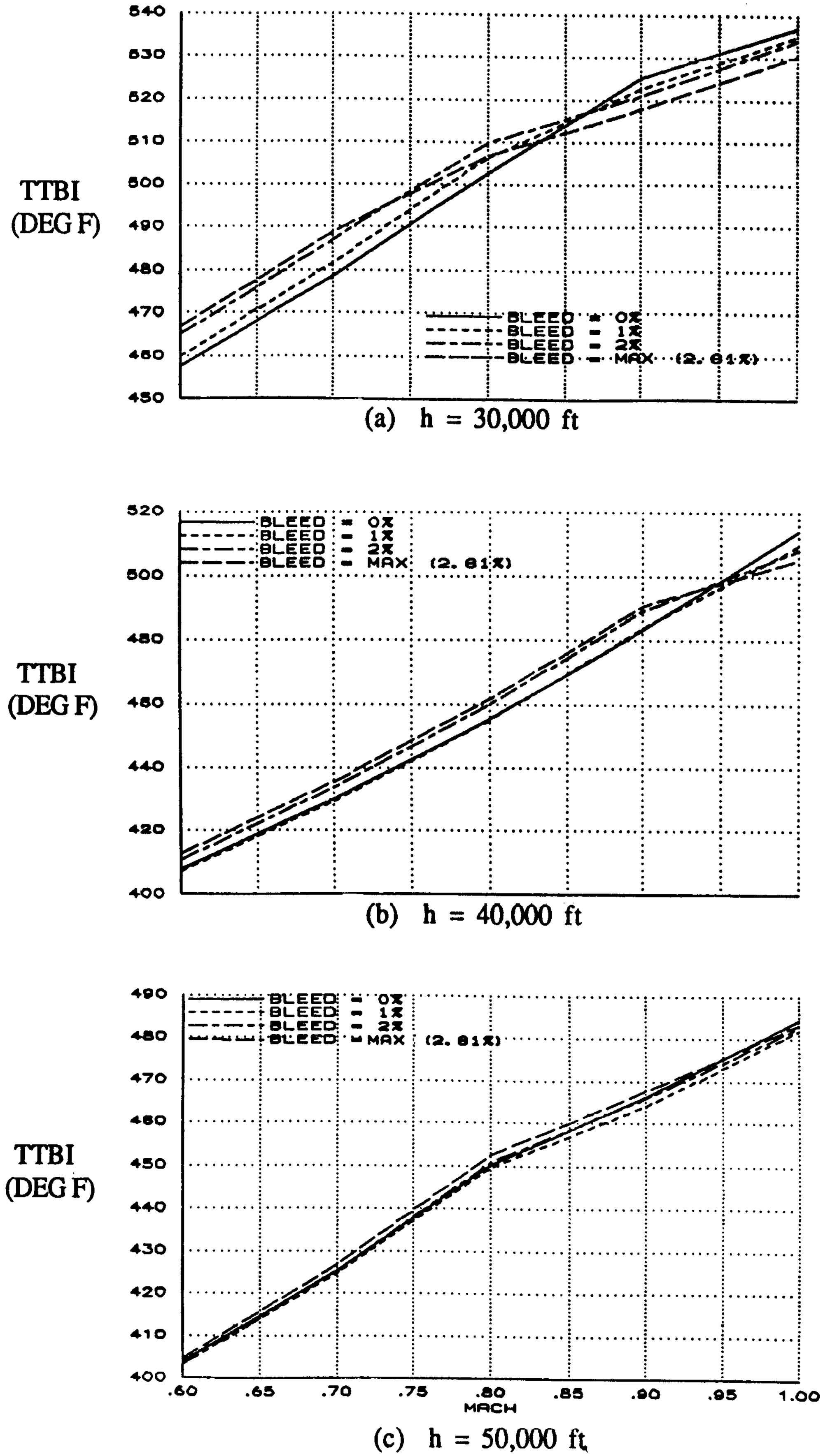


(c) h = 50,000 ft

Figure 7. The effect of Mach and bleed air flow on PTBI; PLA = 130°.

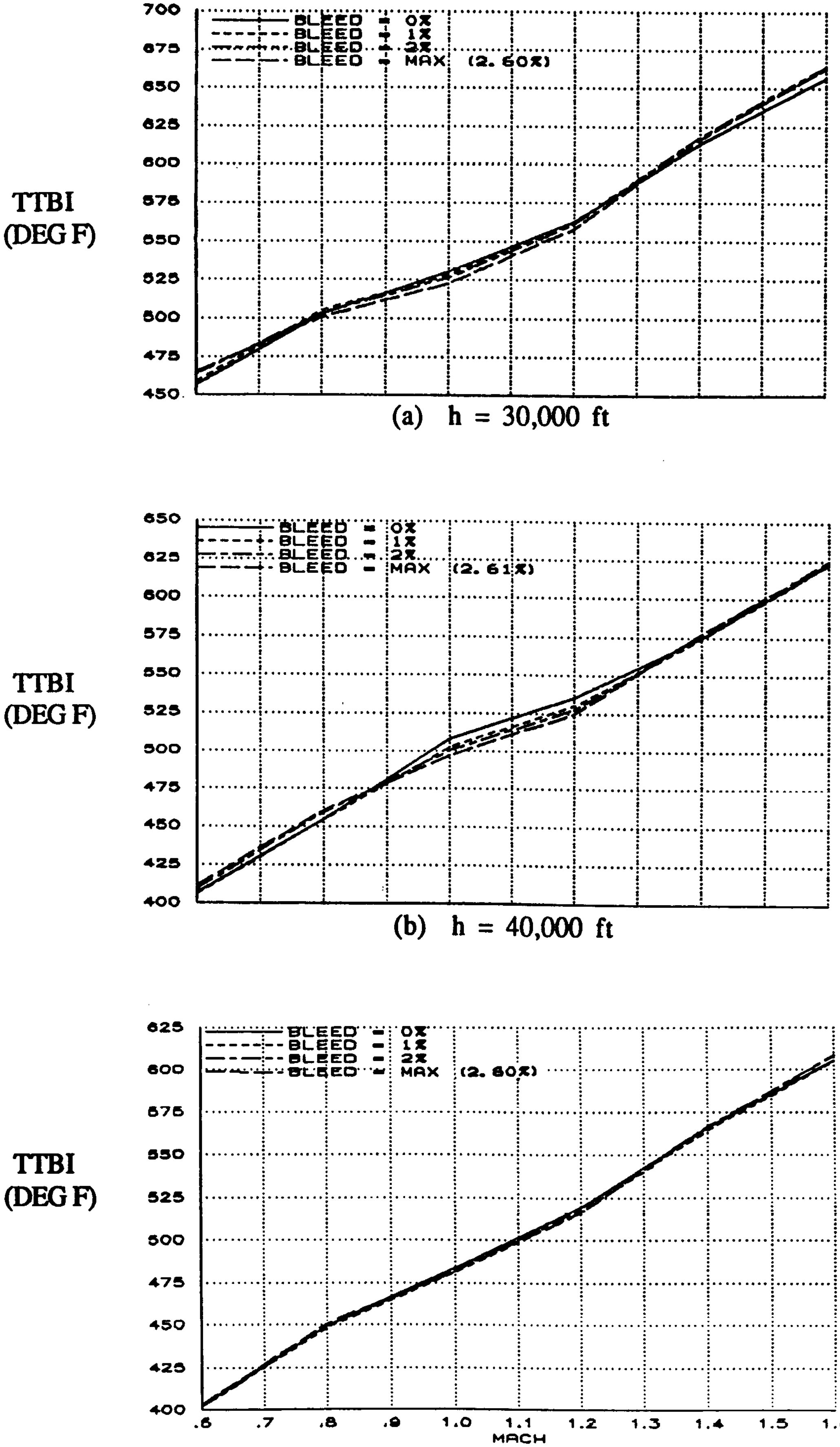


(a) h = 30,000 ft

(b) h = 40,000 ft

(c) h = 50,000 ft

Figure 8. The effect of Mach and bleed air flow on TTBI; PLA = 83°.

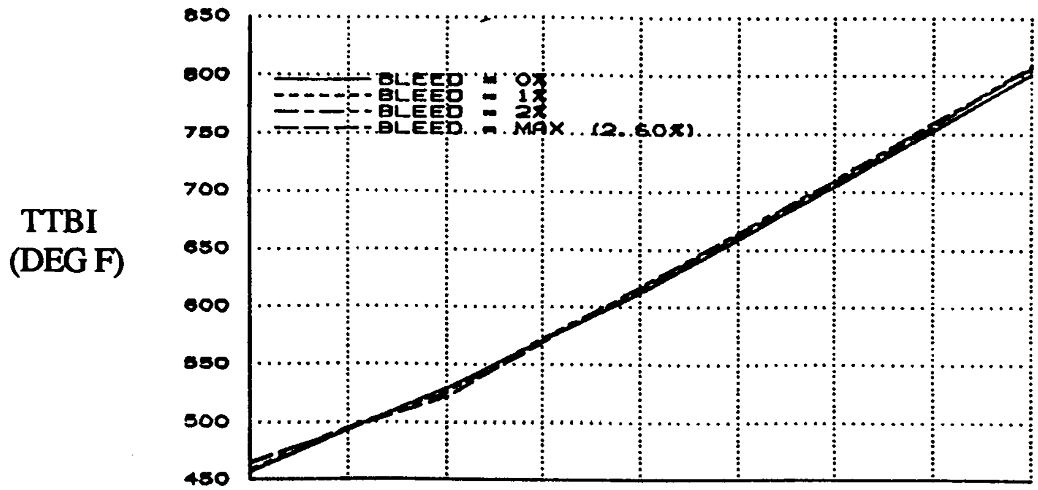


(a) h = 30,000 ft

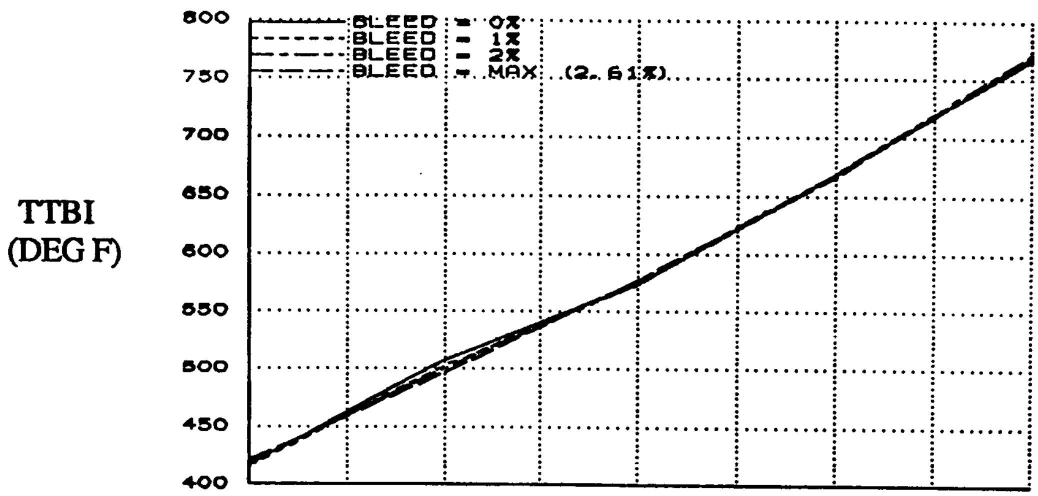
(b) h = 40,000 ft

(c) h = 50,000 ft

Figure 9. The effect of Mach and bleed air flow on TTBI; PLA = 110°.



(a) h = 30,000 ft



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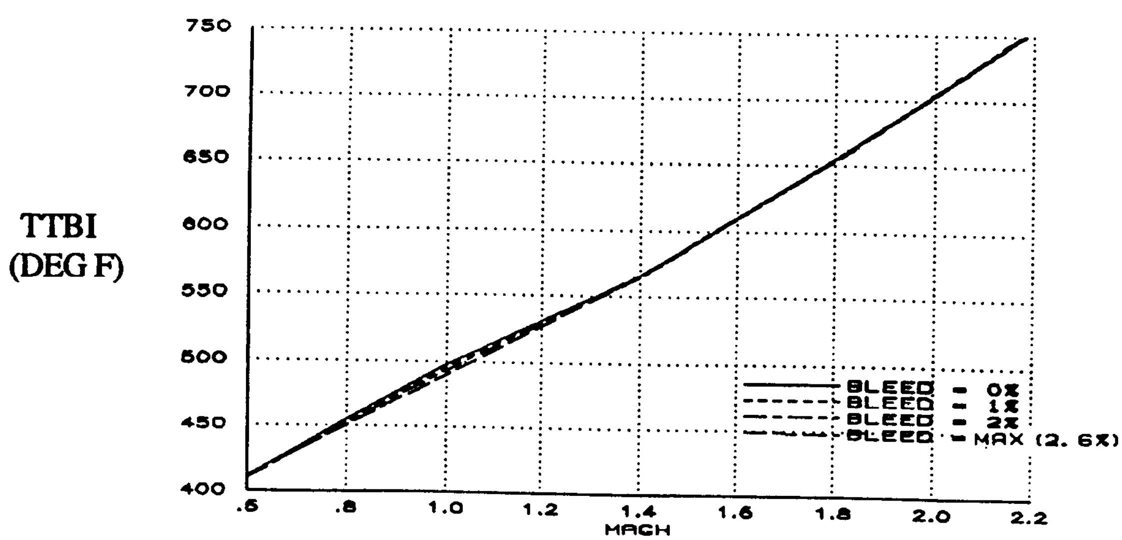
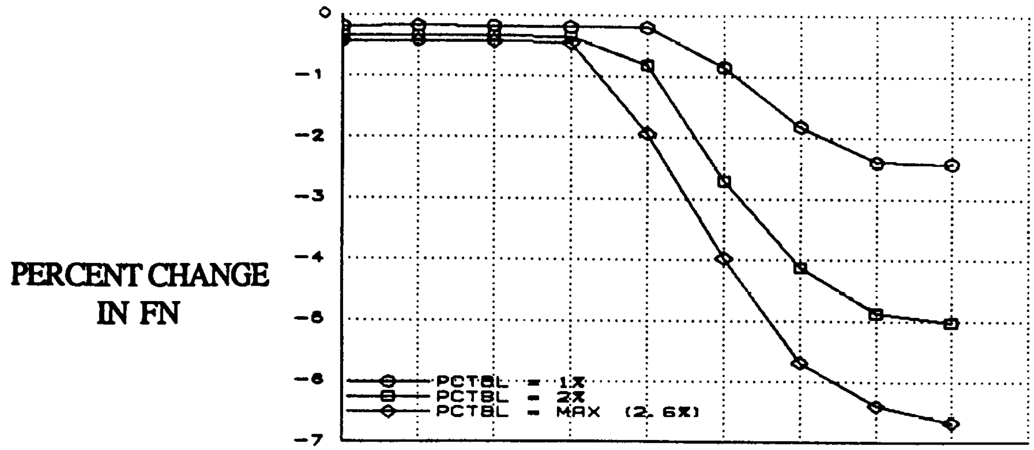
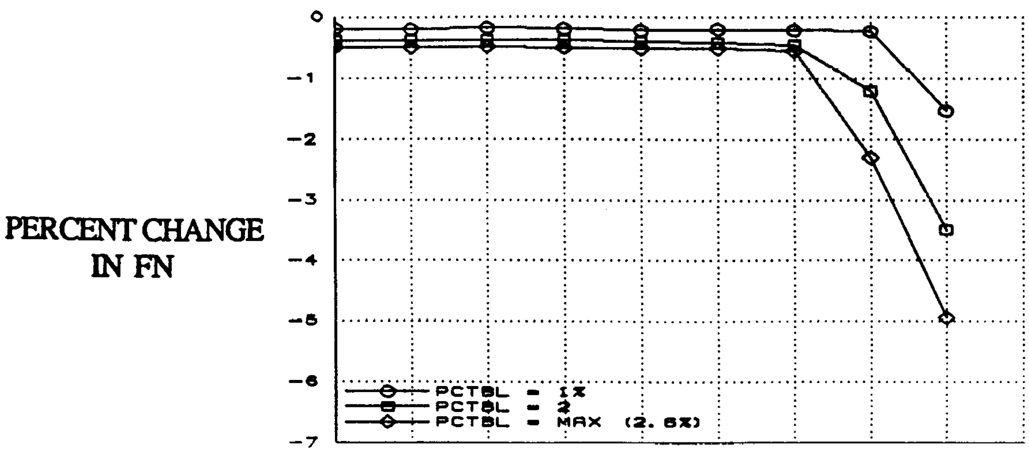


(c) h = 50,000 ft

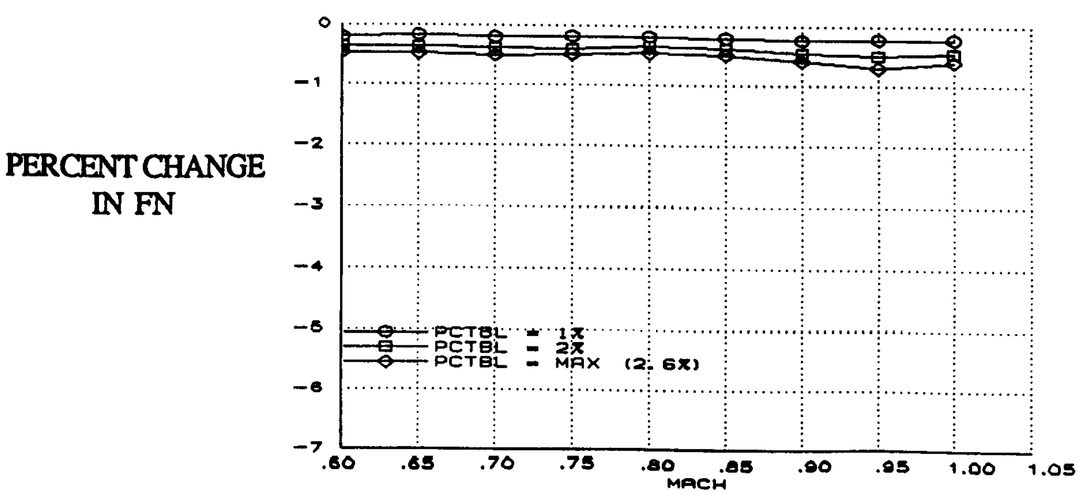
Figure 10. The effect of Mach and bleed air flow on TTBI; PLA =130°.



(a) h = 30,000 ft

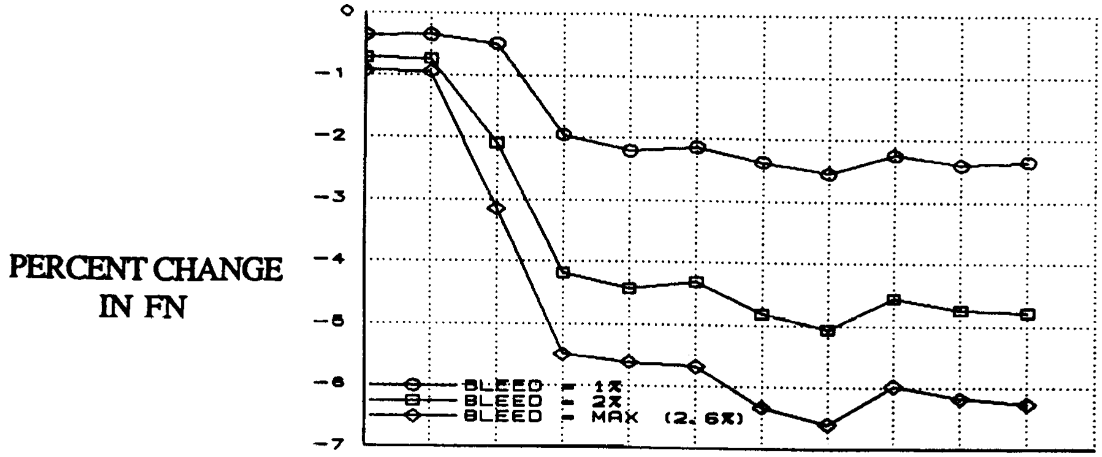


(b) h = 40,000 ft

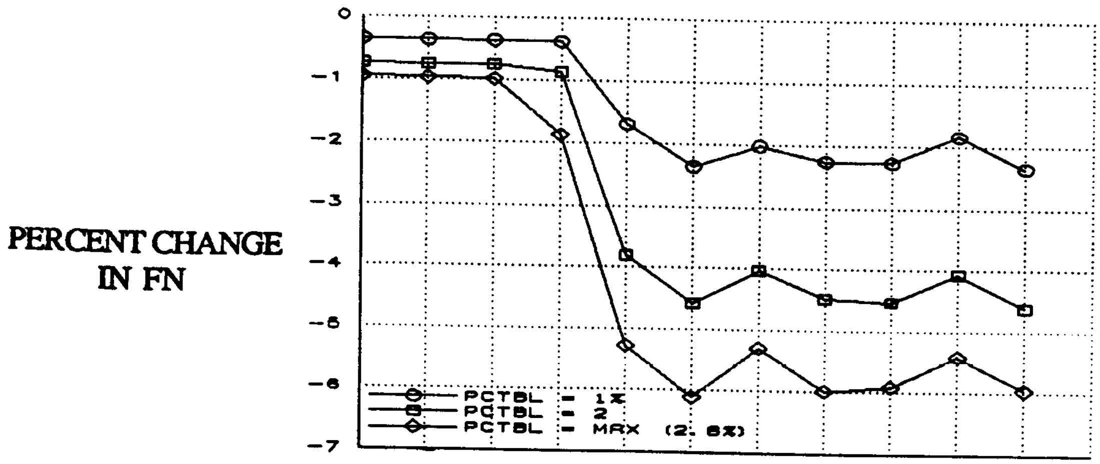


(c) h = 50,000 ft

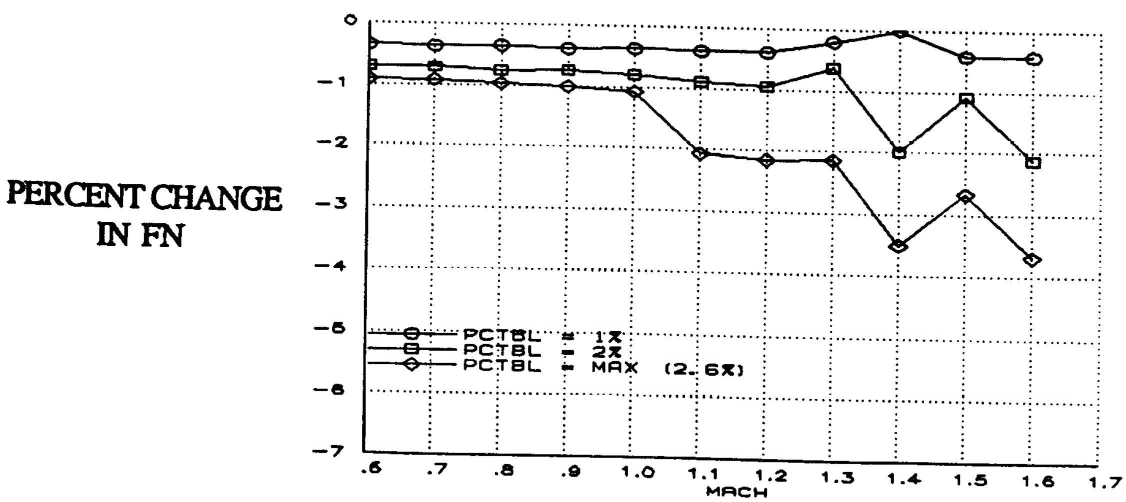
Figure 11. The effect of Mach and bleed air flow on FN; PLA = 83°.



(a) h = 30,000 ft



(b) h = 40,000 ft



(c) h = 50,000 ft

Figure 12. The effect of Mach and bleed air flow on FN; PLA = 110°.

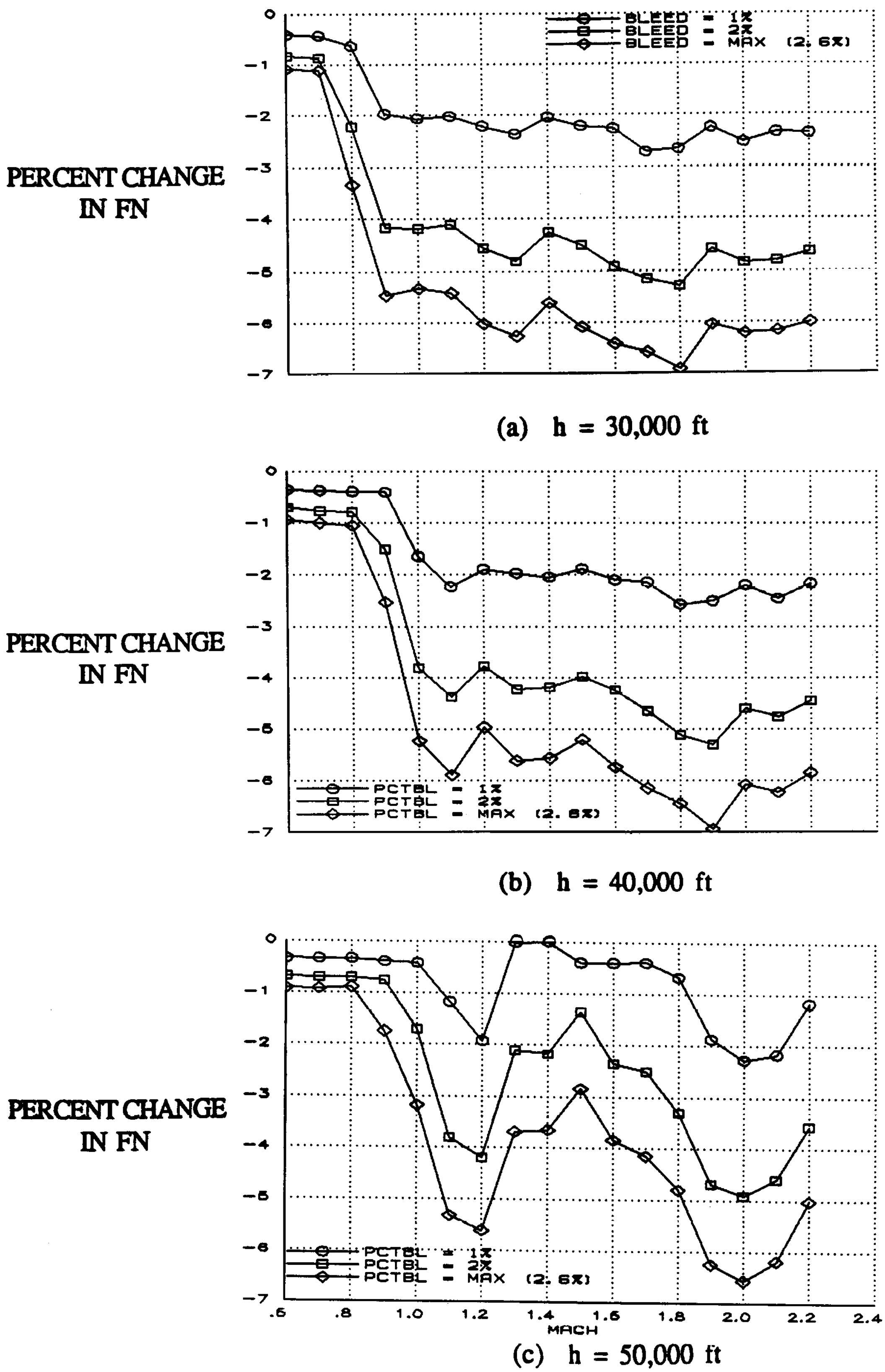
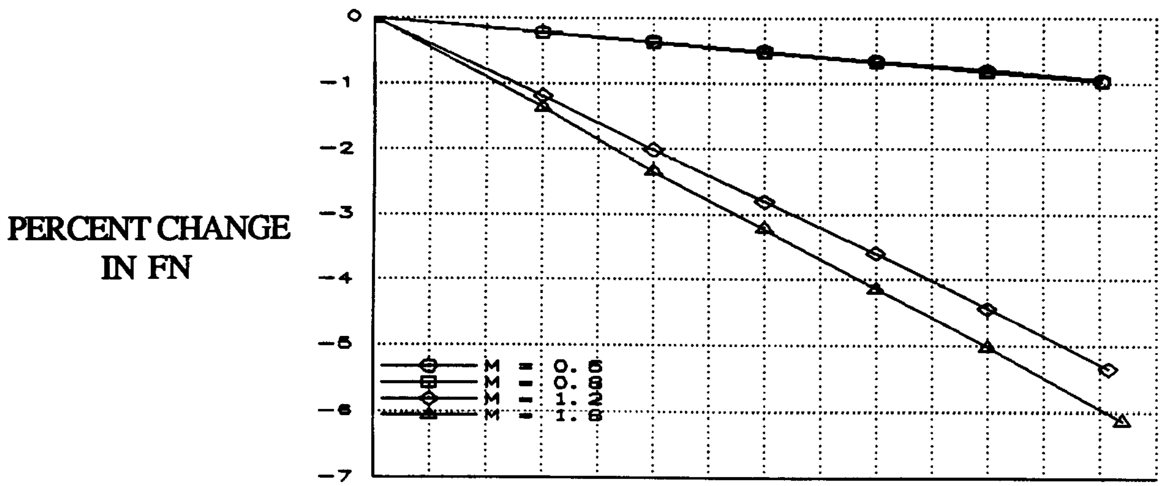
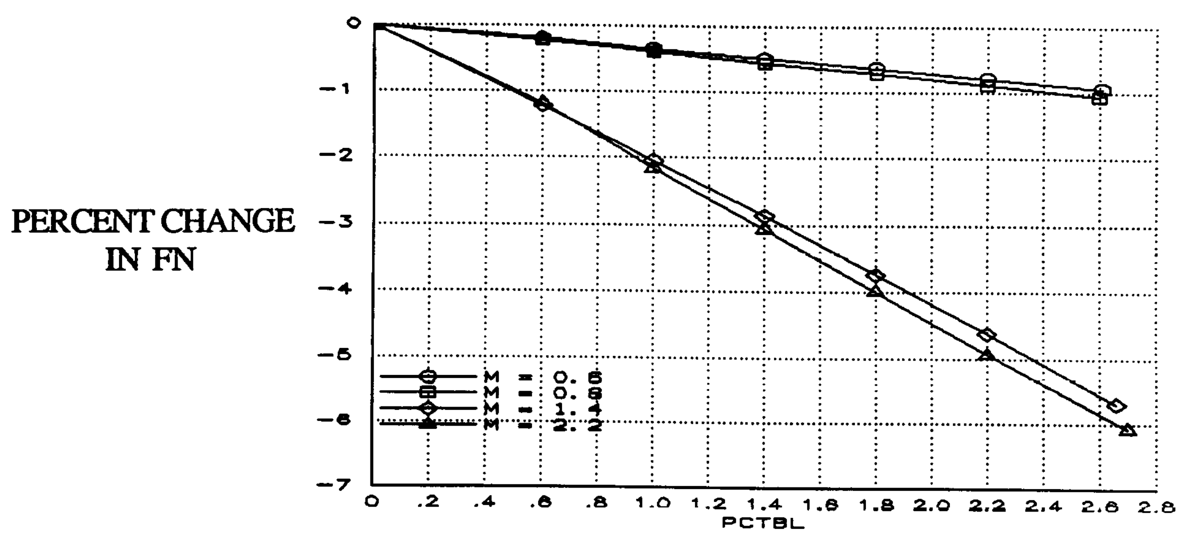


Figure 13. The effect of Mach and bleed air flow on FN; PLA = 130°.



(a) PLA = 110°



(b) PLA = 130°

Figure 14. The effect of bleed and M on FN; h = 40,000 ft.

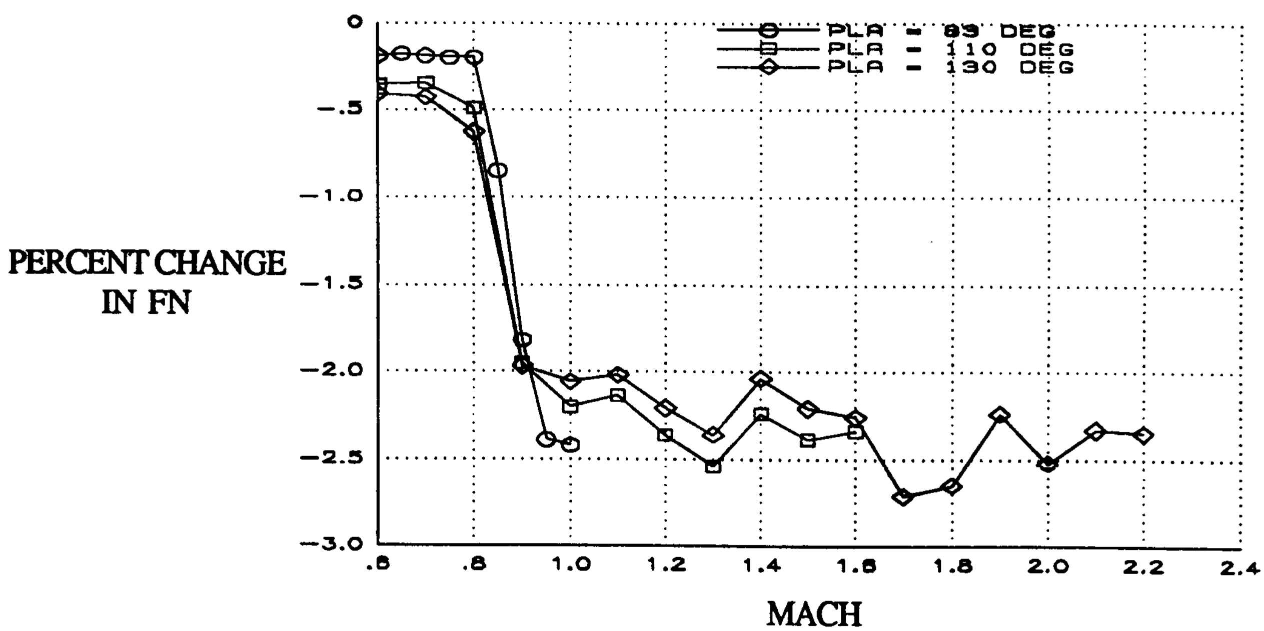
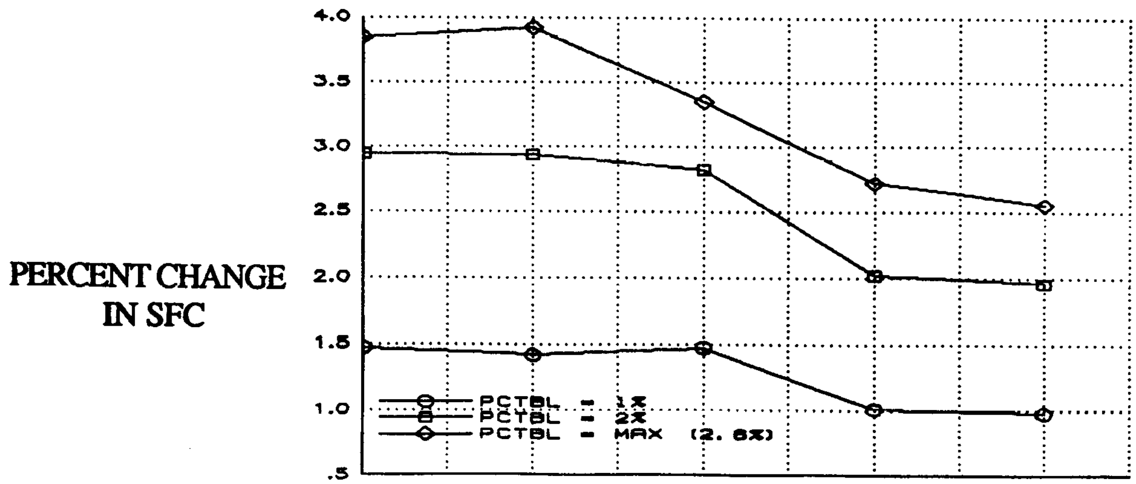
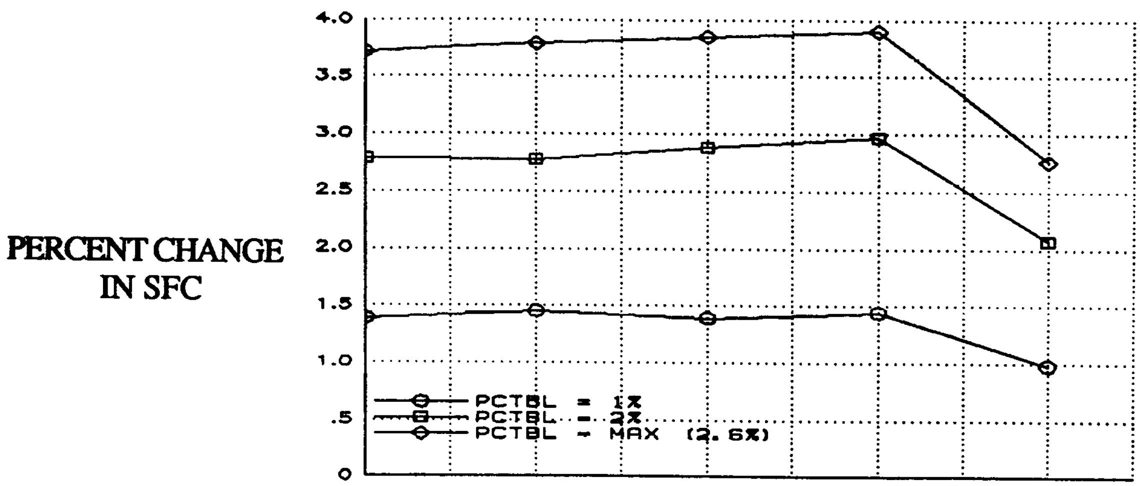


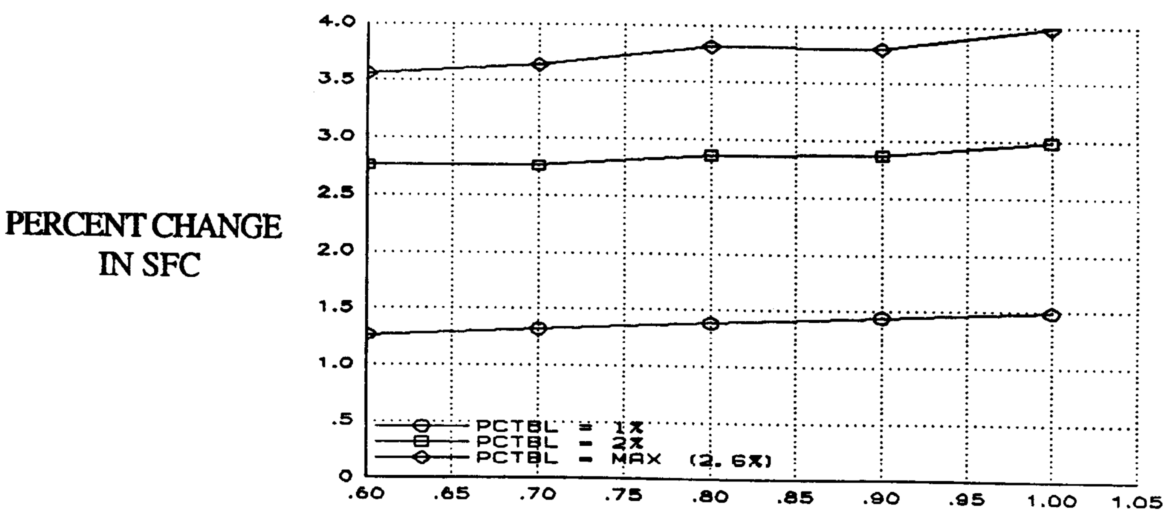
Figure 15. The effect of PLA on percent change in FN; h = 30,000 ft, PCTBL = 1%.



(a) h = 30,000 ft

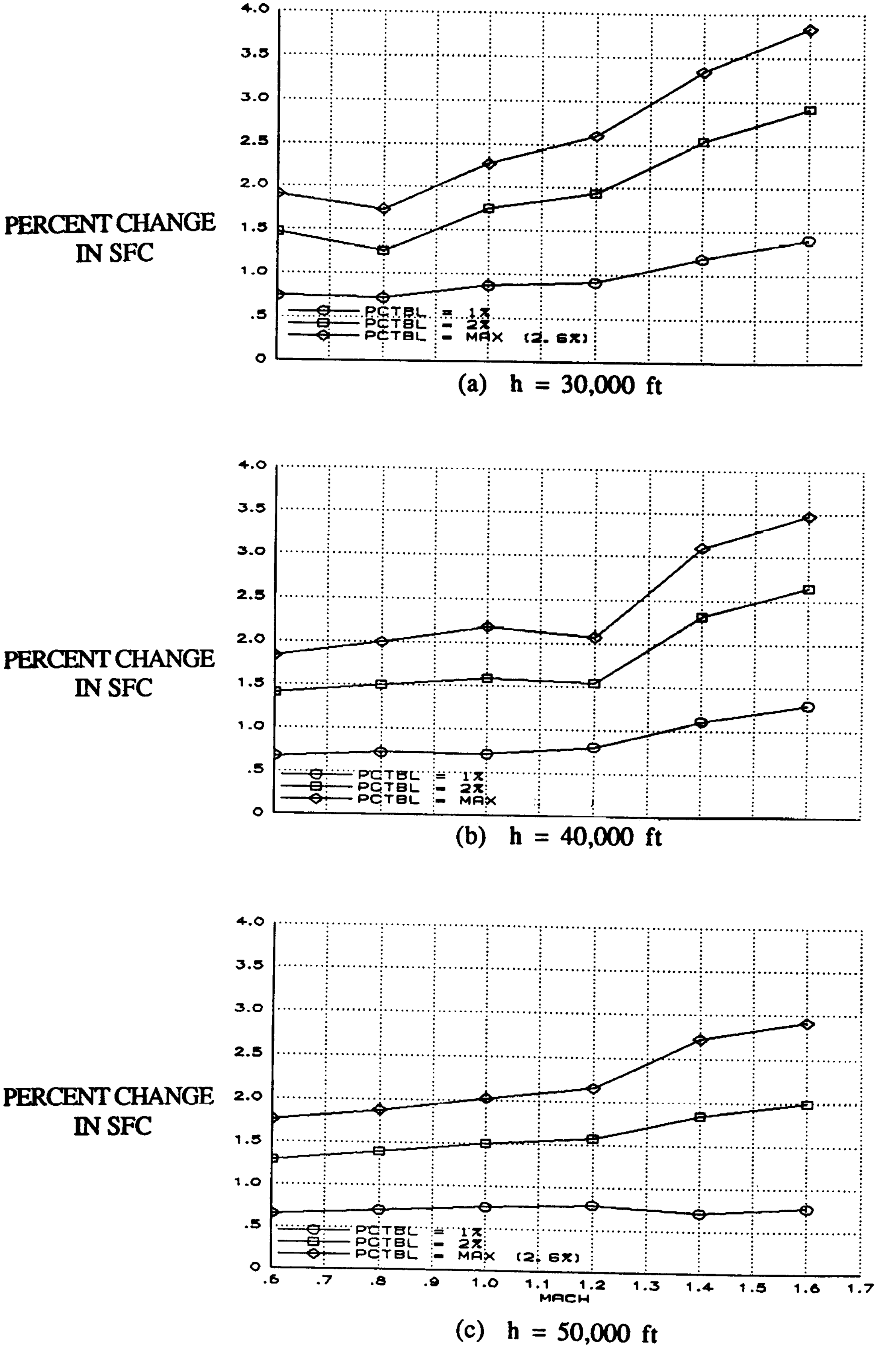


(b) h = 40,000 ft



(c) h = 50,000 ft

Figure 16. The effect of Mach and bleed air flow on SFC; PLA = 83°.

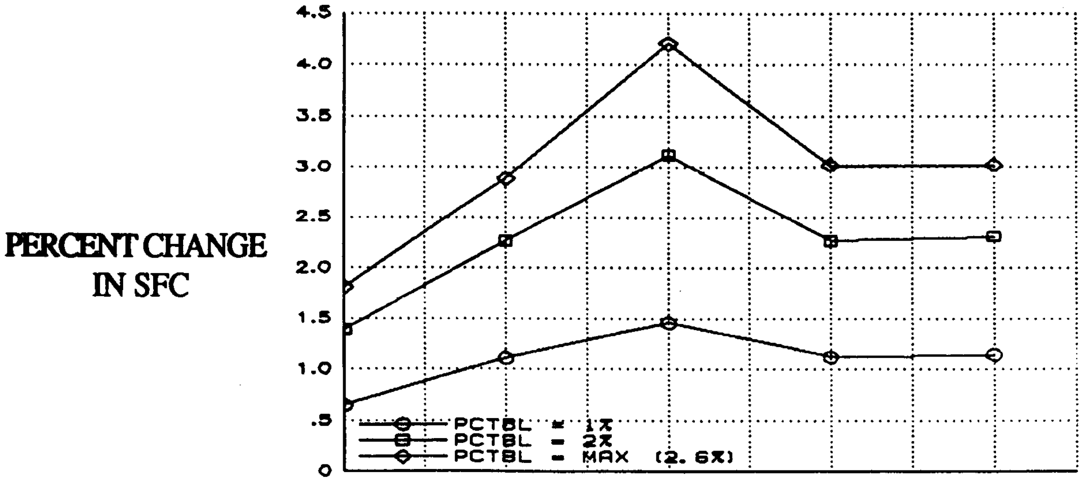


(a) h = 30,000 ft

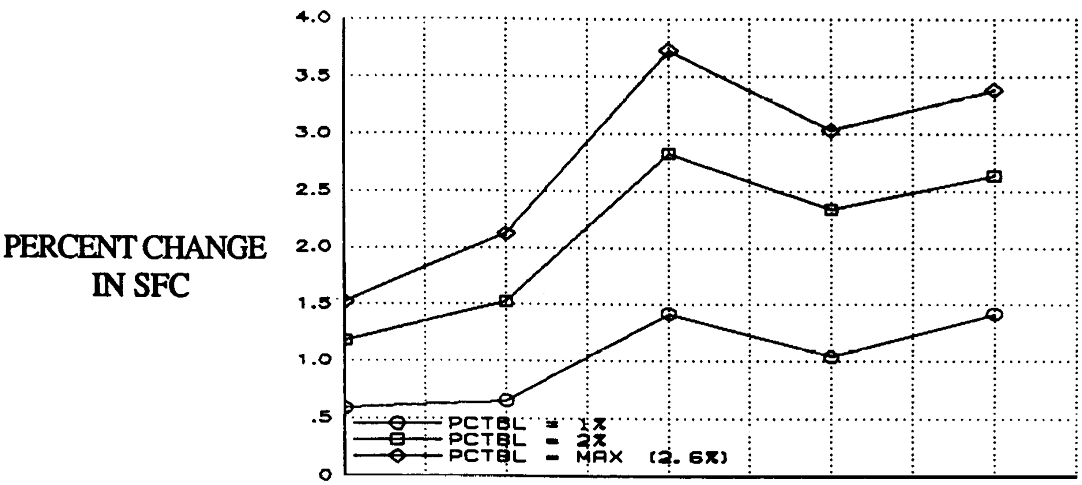
(b) h = 40,000 ft

(c) h = 50,000 ft

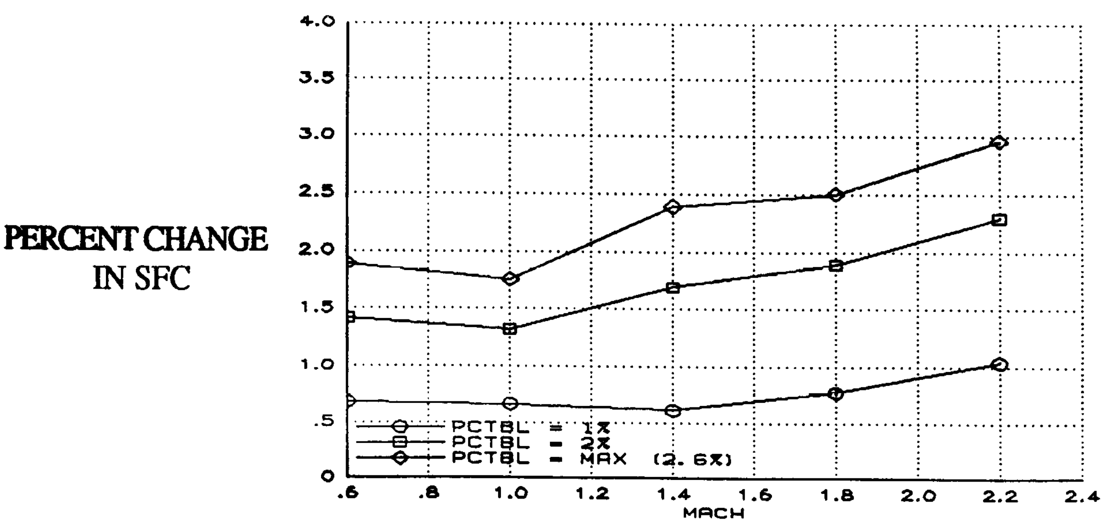
Figure 17. The effect of Mach and bleed air flow on SFC; PLA = 110°.



(a) h = 30,000 ft

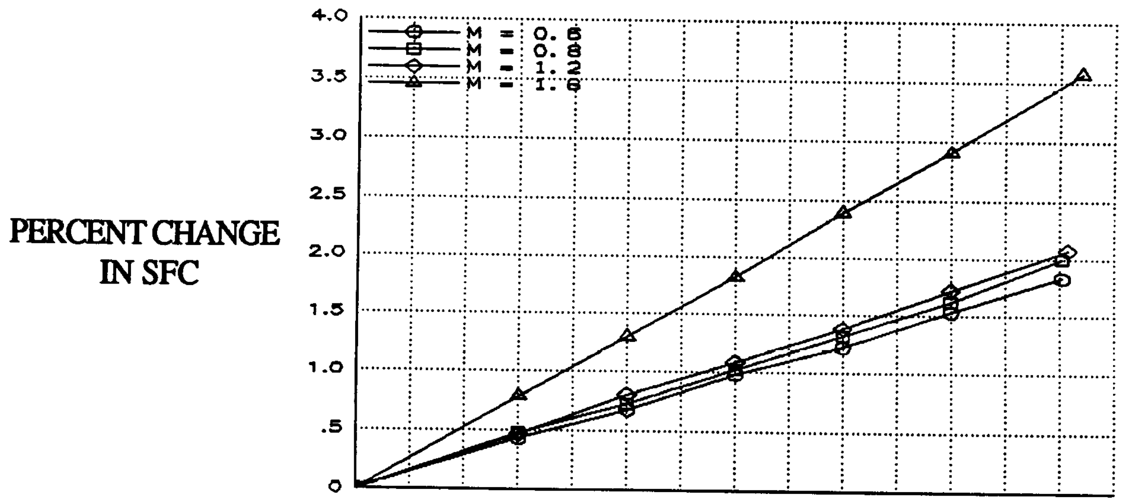


(b) h = 40,000 ft

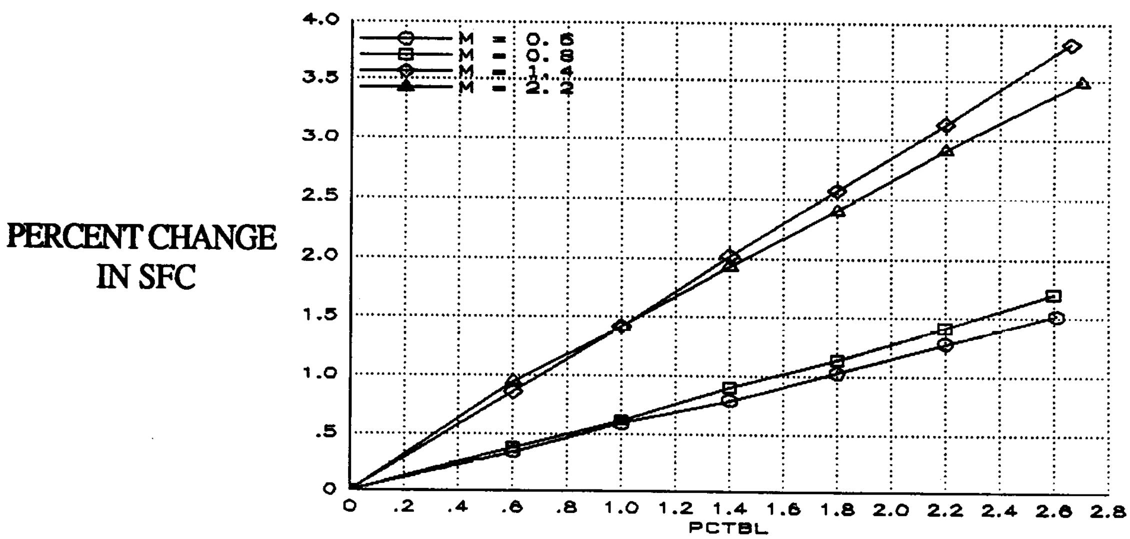


(c) h = 50,000 ft

Figure 18. The effect of Mach and bleed air flow on SFC; PLA = 130°.



(a) PLA = 110°



(b) PLA = 130°

Figure 19. The effect of bleed and M on SFC; h = 40,000 ft.

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15. Supplementary Notes

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16. Abstract

A study has been conducted to determine the effects of seventh-stage compressor bleed on the performance of the F100 afterburning turbofan engine. The effects of bleed on thrust, specific fuel consumption, fan turbine inlet temperature, bleed total pressure, and bleed total temperature were obtained from the engine manufacturer's status deck computer simulation for power settings of intermediate, partial afterburning, and maximum afterburning; for Mach numbers between 0.6 and 2.2; and for altitudes of 30,000, 40,000, and 50,000 ft. It was found that thrust loss and specific fuel consumption increase were approximately linear functions of bleed flow, and, based on a percent-thrust change basis, were approximately independent of power setting.

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